
Production of ECCO-GODAE ocean state estimates and their application to studies of decadal variability

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Estimating the Circulation and Climate of the Ocean (ECCO)

<http://ecco-group.org>

<http://mitgcm.org>



Outline

1. ECCO-GODAE goal: dynamically consistent state estimation via Lagrange multiplier method (closed property budgets)
2. Application of the decadal production (1992-2007) to sea-level
3. Application for observing system design
4. Application for sensitivity studies
5. Toward the coupled ocean/sea-ice problem
6. Toward higher-resolution

State estimation - an early vision, ca. 1982:

Acoustic Tomography and Other Answers

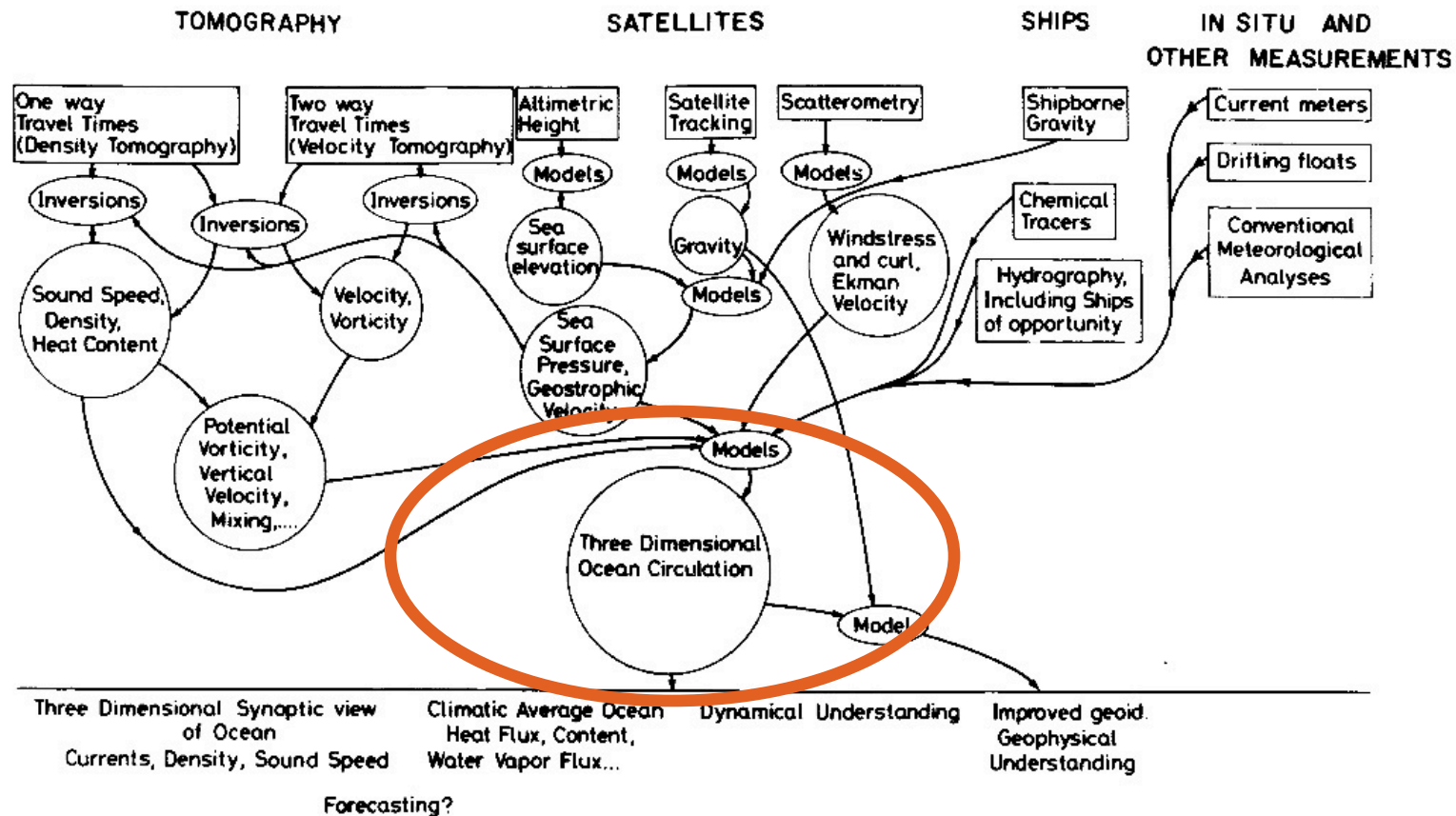
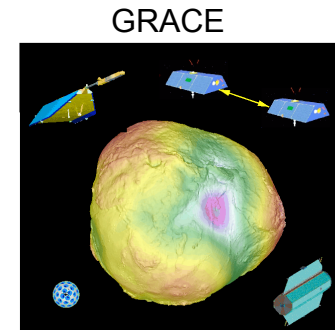
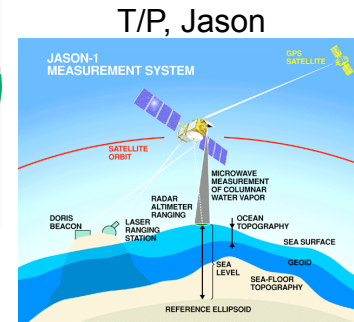
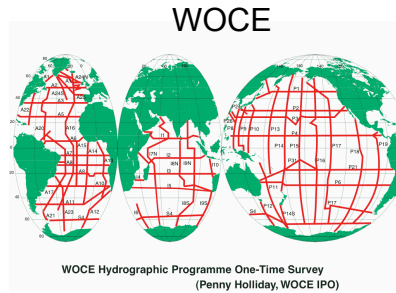
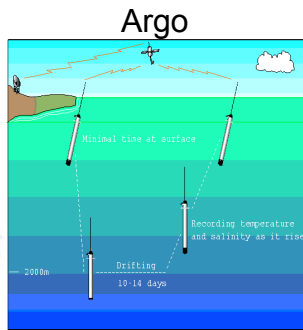


Figure 26. All measurements and models of the ocean can be interconnected to provide global estimates of the state of the three-dimensional ocean. Some side benefits accrue — e.g. improved estimates of the earth's gravity field.

Taken from: **C. Wunsch**, in "A Celebration in Geophysics and Oceanography 1982. In Honor of Walter Munk on his 65th birthday."

C. Garrett and C. Wunsch, Eds., [SIO Reference Series 84-5](#), March 1984

Ocean State Estimation

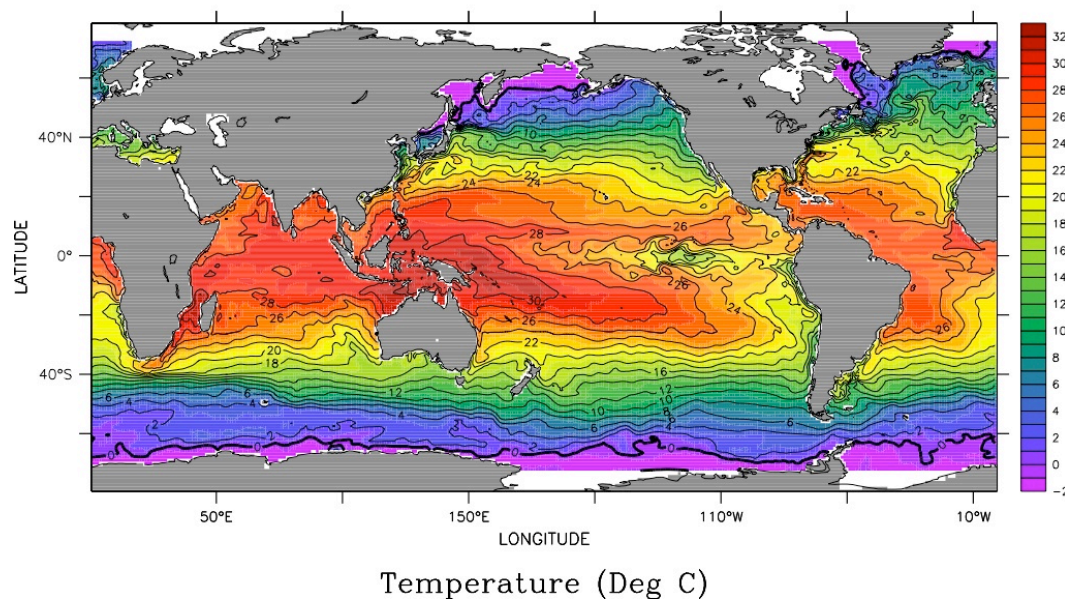


How to synthesize? Estimation/optimal control problem:
Use a **model** (MITgcm) and its **adjoint**:

DEPTH (m) : 5
TIME : 01-JAN-2000 00

DATA SET: Tave

Assimilation (Adjoint) by ODAP



The observations

observation	instrument	product	area	period	dT	#
Mean dynamic topography (MDT)	<ul style="list-style-type: none"> GRACE GGM02 GRACE SM004-GRACE3 	U-Texas (B. Tapley) CLS/GFZ (A.M. Rio)	global global	time-mean	time-mean	3.2E4
Sea level anomaly (SLA)	<ul style="list-style-type: none"> T/P, Jason ERS, ENVISAT GFO 	PO.DAAC AVISO NOAA, USN	66°N/S 82°N/S 65°N/S	1992 - 2006 1992 - 2006 2001 - 2004	daily daily daily	1.7E7 1.2E7 6.6E6
SST	<ul style="list-style-type: none"> blended, AVHRR (O/I) TRMM/TMI AMSR-E (MODIS/Aqua) 	Reynolds & Smith (1999) NASA, NOAA NASA, NOAA	Global 40°N/S	1992 - 2006 1998 - 2003 2001 - 2006	monthly monthly monthly	6.5E6 2.9E6
SSS	In-situ, ships	ECOP (France)	Pacific	1992 - 1999	monthly	2.4E4
In-situ T, S	<ul style="list-style-type: none"> Argo, P-Alace XBT CTD SEaOS TOGA/TAO, Pirata 	Ifremer, ... S. Behringer (NCEP) Various SMRU & BAS (UK) PMEL/NOAA	"global" "gobal" sections SO Trop. Pac.	2003 - 2006 1992 - 2006 1992 - 2006 1992 - 2006	daily daily daily daily daily	2.1E7 1.0E7 2.0E6 5.2E5 3.3E6
Mooring velocities	<ul style="list-style-type: none"> TOGA/TAO, Pirata RAPID 	PMEL/NOAA SOC (UK)	Trop. Pac. N. Atl.	1992 - 2006 3/2004 - 5/2005	daily daily	2 x 1.1E6
Climatological T,S	<ul style="list-style-type: none"> WOA01 (upper 300 m) WOCE 	Conkright et al., 2002 Gouretski & Koltermann, 2004	"global" "global"	1950 - 2000 1950 - 2002	time-mean time-mean	2 x 8.1E6
Wind stress	QuickScat	NOAA, NASA	global	1999 - 2004	2-day	2 x 4.7E6
Tide gauge SSH	Tide gauges	NBDC/NOAA	sparse	1992 - 2006	monthly	5.5E4
Flux constraints	NCEP/NCAR variances	Kalnay et al., 1997	global	1992 - 2006	2-day	4 x 2.0E8
Balance constraints			global	1992 - 2006	time-mean	2 x 3.6E5
bathymetry		Smith & Sandwell, ETOPO5	global	-	-	

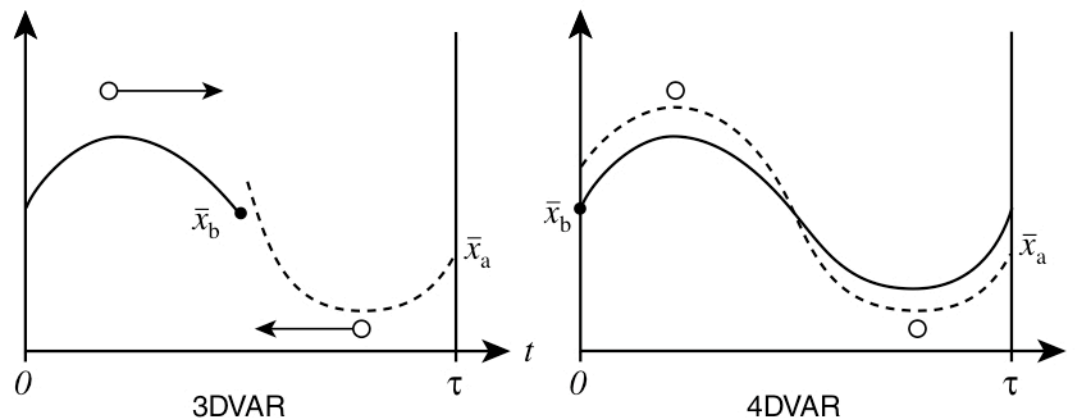
Data assimilation: The estimation (interpolation) vs. the forecasting (extrapolation) problem

- **Atmosphere**

- Relatively abundant data sampling of the 3-dim. atmosphere
- Most DA applications target the problem of optimal forecasting
 - find initial conditions which produce best possible forecast;
 - *no dynamical consistency required on climate time scales*

- **Ocean**

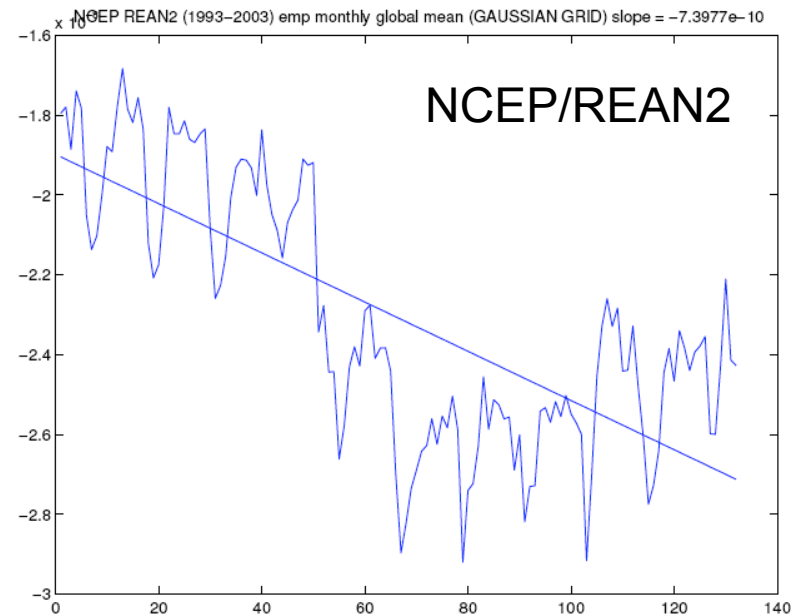
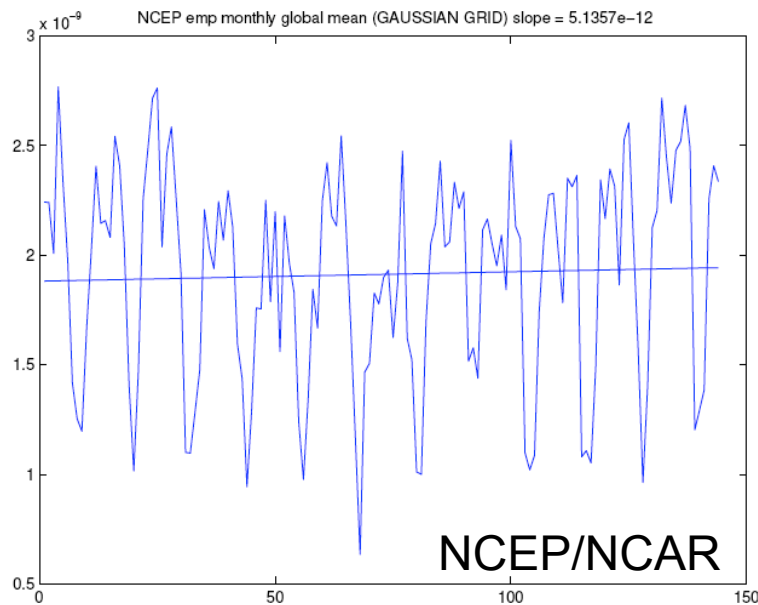
- Very sparse data sampling of the 3-dim. ocean
- Trying to understand the past & present state of the ocean is a major issue all by itself, the forecasting maybe secondary (note also the comparatively slow timescales of oceanic processes)
 - use available observations in an optimal way to extract information about the ocean state
 - *dynamic consistency essential over climate time scales*



Why does it matter: (Huge) imbalances in (all) atmospheric “re-analysis” products

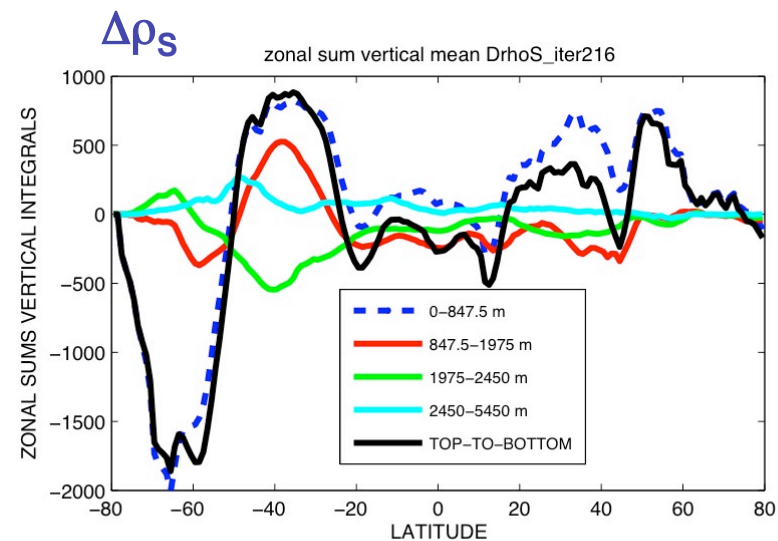
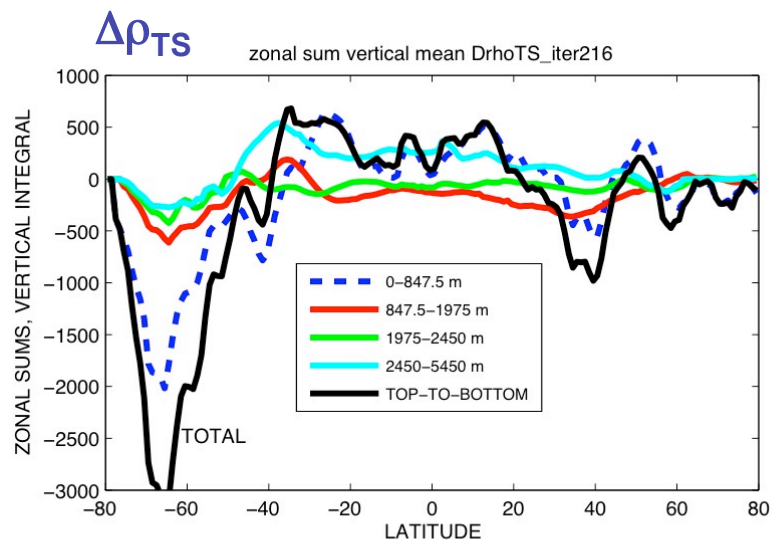
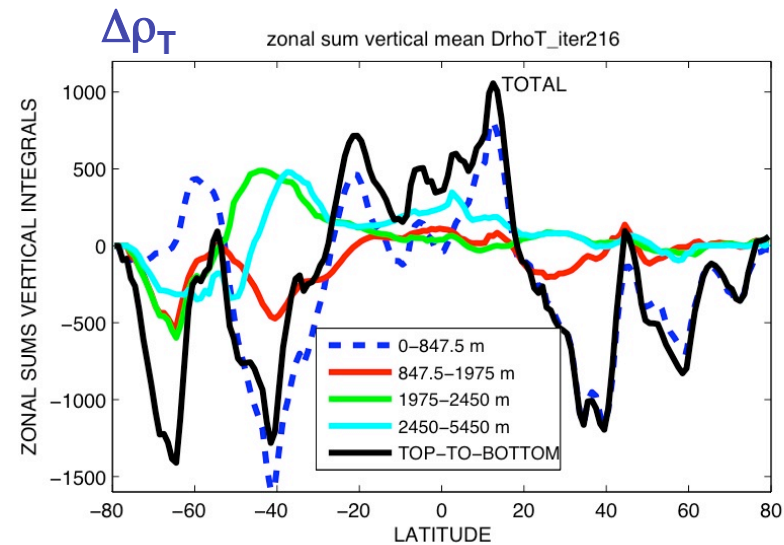
Need to remove air-sea flux imbalances

	mean [cm/year]	intercept [mm/sec]	slope [mm/sec ²]
NCEP/NCAR-I ocean $E - P$	15.1	4.90E-9	9.29E-12
NCEP/NCAR-I ocean $E - P - R$	6.2	1.92E-9	9.29E-12
NCEP/NCAR-I global $E - P$	6.1	$\sim 1.90\text{E-}9$	5.14E-12
NCEP/DOE-II global $E - P$	-73.9	$\sim -19.00\text{E-}9$	-740.00E-12



Application: Decadal sea-level patterns and their top-to-bottom partition

- Vertical partition in density trends due to
 - trends in temperature T
 - trends in salinity S
 - trends in T, S



Wunsch et al., 2007 (J. Clim.): Decadal trends in sea level patterns

Observing system experiments (OSE):

Exploring state estimation systems to assess observation impact

- **Rationale:**

evaluate impact of different observing types, as well as their spatio-temporal distributions

- In particular, focus on

- role of elements of the global observing system (altimetry, satellite SST, Argo)
- impact on climate diagnostics, here MOC

- **Approach:**

- data withholding experiments using the ECCO state estimation system
- based on 1-yr experiments to limit sampling-related issues

- **An aside:**

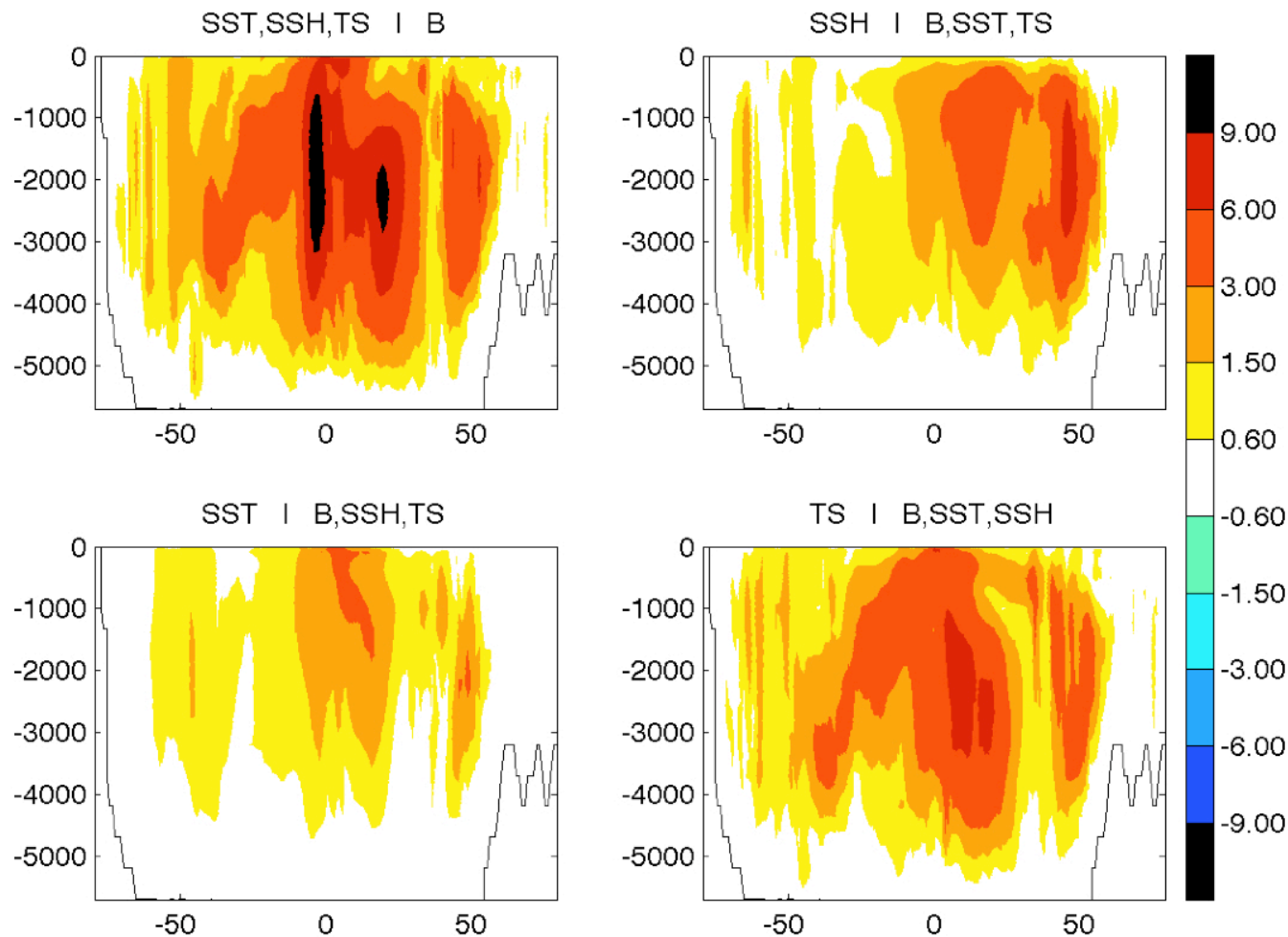
- Extensive use and (more advanced) approaches in the context of numerical weather prediction (NWP)

Observing system experiments (OSE):

Exploring state estimation systems to assess observation impact

RMS variability differences in MOC from state estimates using different data ingredients
(baseline B is an estimate that is fit to only hydrographic climatology, WOA01)

Notation: $\mathbf{j} \mid \mathbf{B}, \mathbf{x}, \mathbf{y}, \dots$: \mathbf{j} is newly added data to prior $\mathbf{B}, \mathbf{x}, \mathbf{y}, \dots$



B: baseline

SSH: altimetry

TS: Argo

SST: satellite SST

Main results:

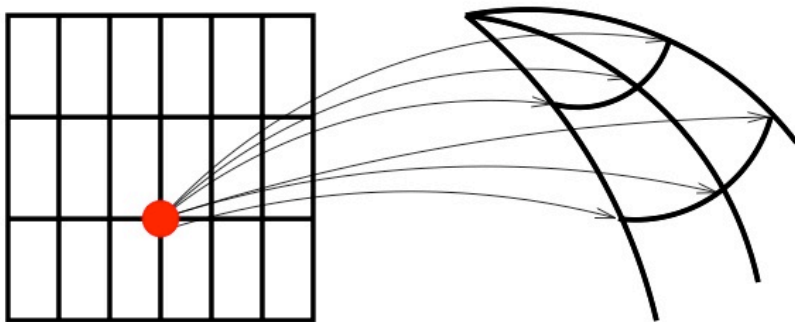
- (1) Large impact of altimetry & Argo
- (2) Climatology yields poor constraint
- (3) Complementary nature of Argo, altimetry
- (4) Modest impact of SST

*(Forget et al,
In preparation)*

Sensitivity calculations in forward or reverse

► Finite difference approach:

- Take a “guessed” anomaly (SST) and determine its impact on model output (MOC)
- Perturb each input element (SST(i, j)) to determine its impact on output (MOC).



Impact of one input on all outputs

► Reverse/adjoint approach:

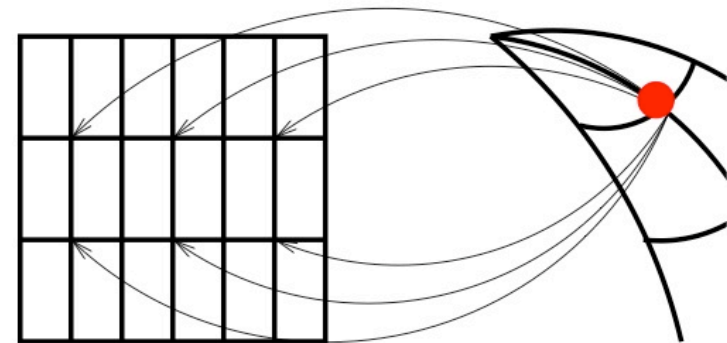
- Calculates “full” sensitivity field

$$\frac{\partial \text{MOC}}{\partial \text{SST}(x, y, t)}$$

- Approach:

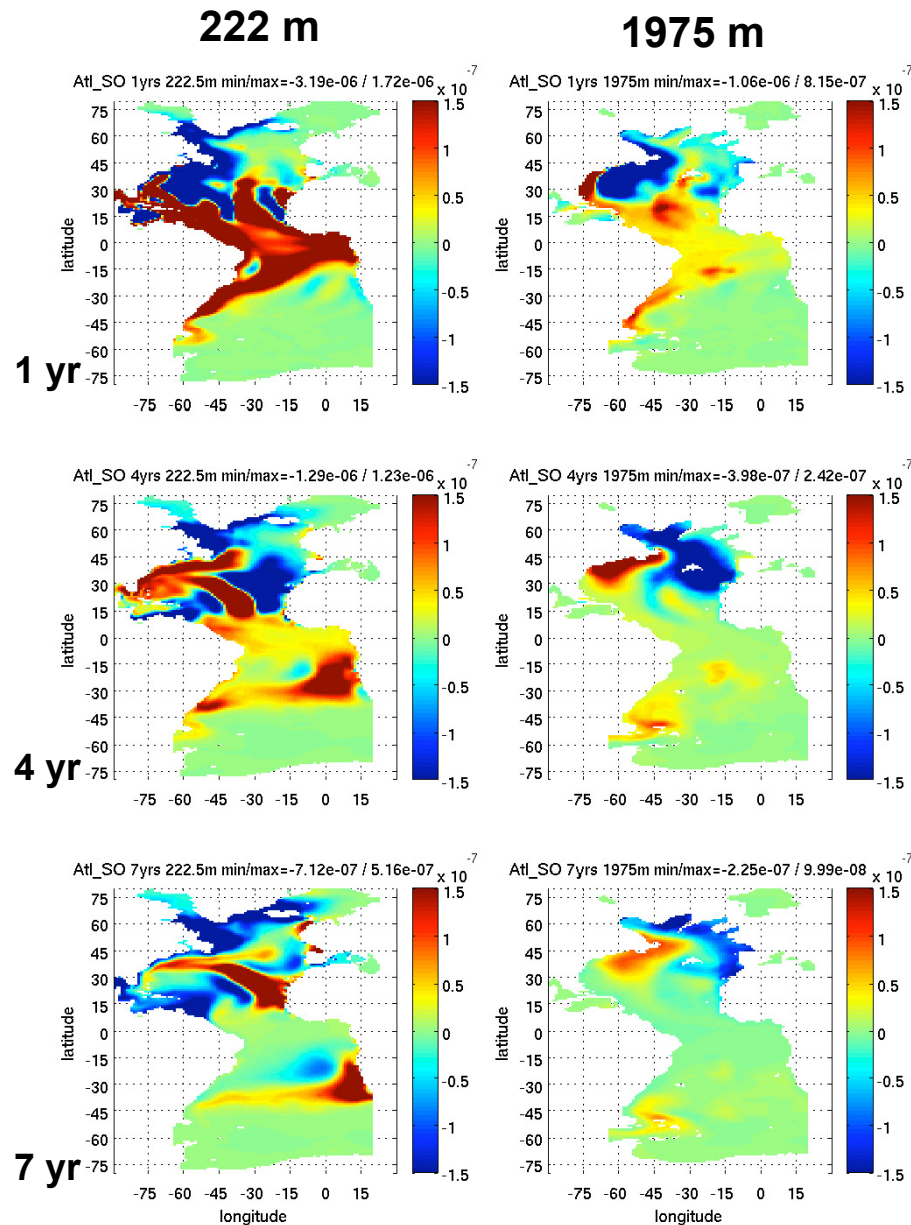
Let $\mathcal{J} = \text{MOC}$, $\vec{u} = \text{SST}(i, j)$

$$\longrightarrow \boxed{\vec{\nabla}_u \mathcal{J}(\vec{u})} = \frac{\partial \text{MOC}}{\partial \text{SST}(x, y, t)}$$



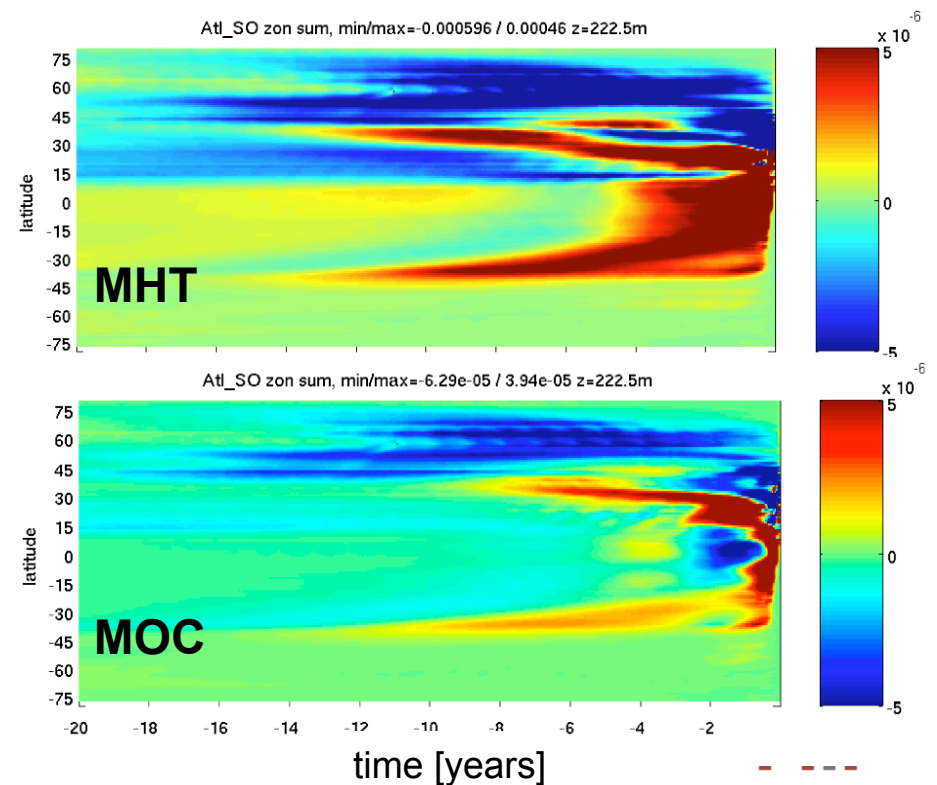
Sensitivity of one output to all inputs

Example: Meridional heat transport sensitivities to temperature perturbations at various depths

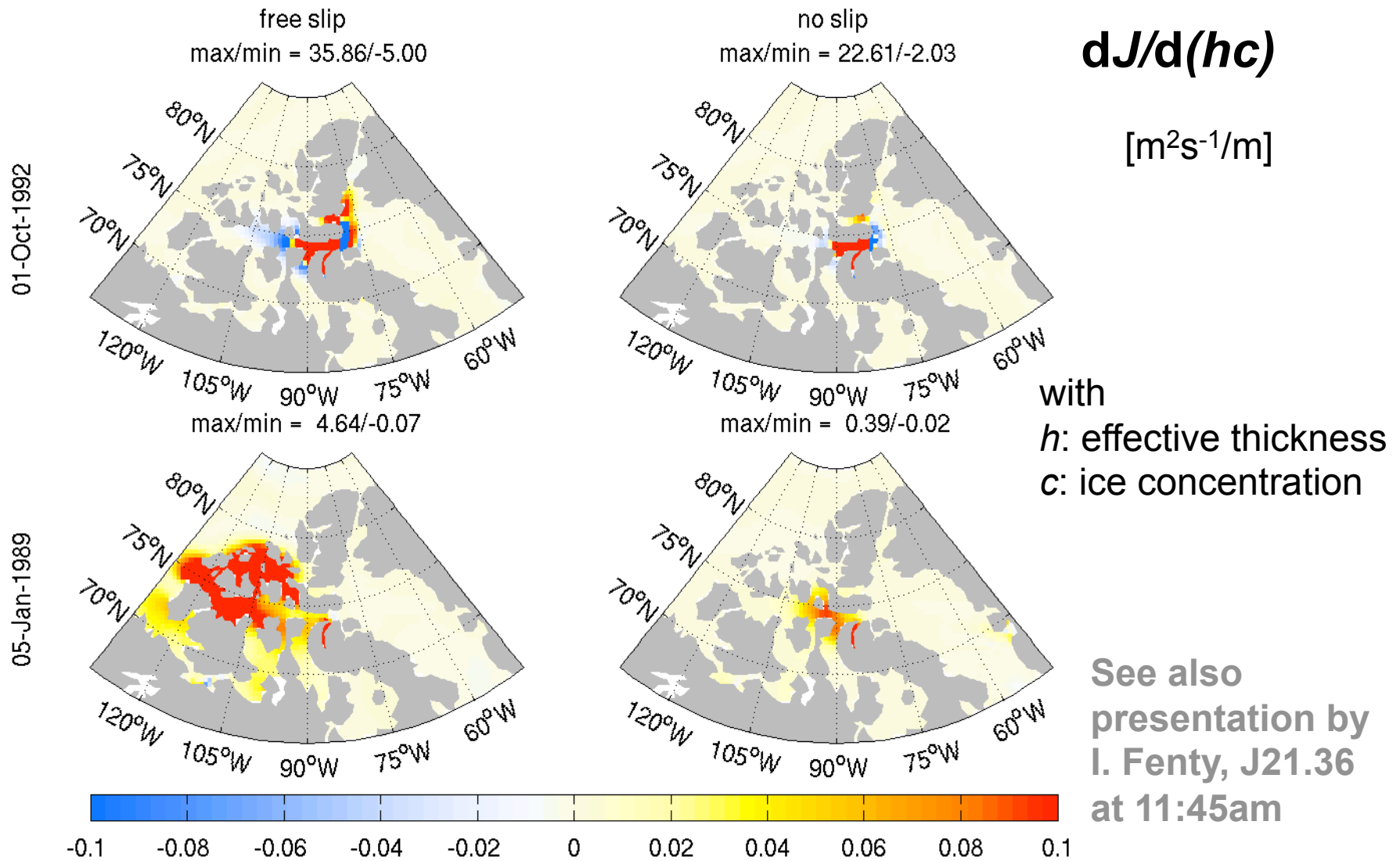


$$\delta J(i, j, k, t) = \left. \frac{\partial J}{\partial X} \right|_{(i, j, k, t)} \cdot \frac{\delta X(i, j, k)}{dz(k)}$$

Cumulative sensitivities for each latitude in the Atlantic back in time (right to left) at 222 m depth



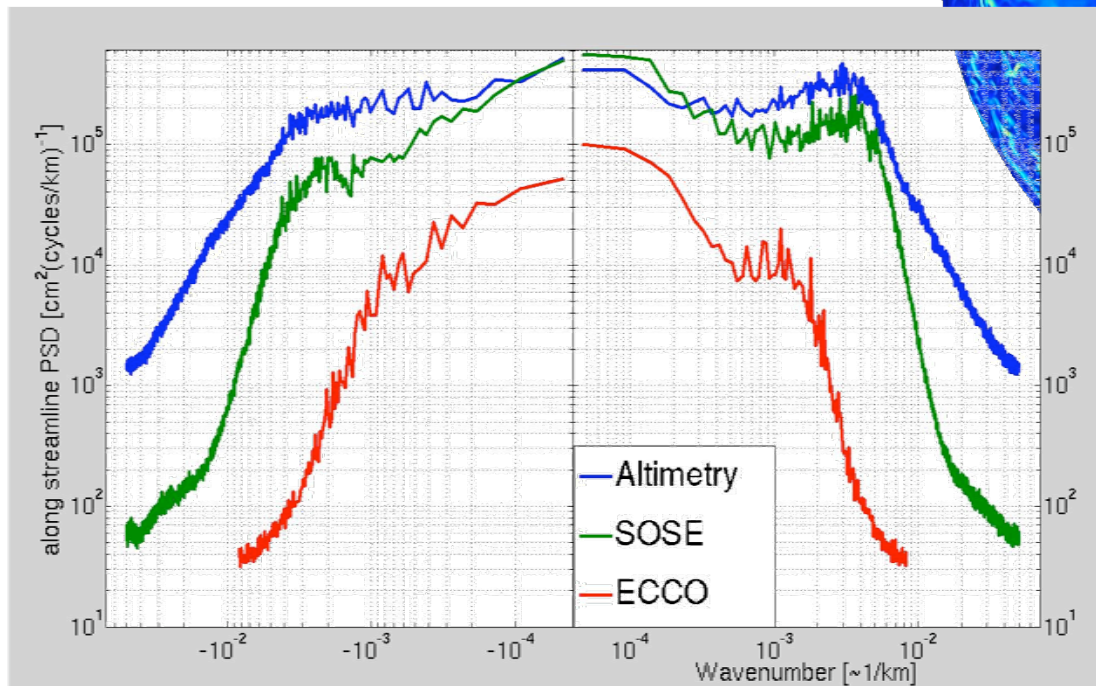
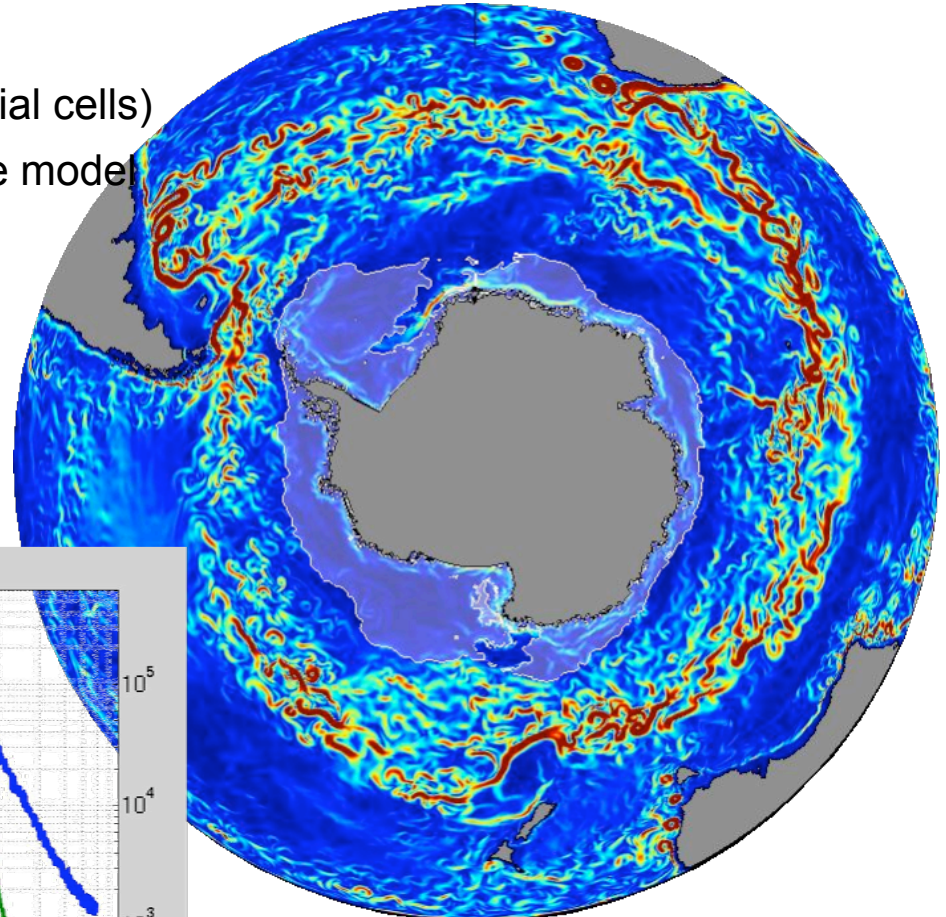
Example: Adjoint sensitivity of solid freshwater transport through Lancaster Sound in the Canadian Arctic Archipelago



Toward high-resolution state estimation: SOSE

An eddy permitting state estimation of the Southern Ocean (M. Mazloff)

- 78° South to 24.7° South
- 1/6° horizontal resolution; 42 depth levels (partial cells)
- atmospheric boundary layer scheme & sea-ice model
- similar setup to ECCO-GODAE
- adjoint generated via AD tool TAF
- KPP, GM/Redi parameterizations
- currently optimizing year 2005 to 2007
- 600 processor adjoint on SDSC's IBM SP4



See also presentation by
D. Menemenlis, J21.35
at 11:30am



Outlook

- ECCO remains primarily directed at mechanistic understanding of climate variability from time-varying ocean state that is consistent with observations and known physics as a necessary prerequisite for prediction.
- Rigorous state estimation using most of the available observations is possible and scientifically useful. Studies so far included
 - Decadal variability in poleward heat and mass transports
 - Regional patterns of sea-level change
 - Driving of biological models with ECCO flow fields
- Application of adjoint and state estimation system should be extended for formal observing system design studies
- ECCO-GODAE now going fully global as coupled ocean/sea-ice system, with increased focus on high latitudes
- Move toward high resolution will continue, both globally (ECCO2), and regionally (Southern Ocean, North Atlantic & Arctic)